Distributed Address Assignment with Address Borrowing for ZigBee Networks

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Abstract—ZigBee is a popular communication standard for wireless sensor networks. It suggests a *distributed address assignment mechanism (DAAM)*, which is easy to implement but may restrict the number of children of a router and the depth of the network. Since DAAM is too conservative, the utilization of the 16-bit address pool may become poor, causing the *orphan problem*. In this paper, we propose a distributed address assignment scheme by allowing a parent to borrow a subtree of address space from a neighbor to alleviate the orphan problem. When a new node tries to associate with a parent router which has no free address, this parent router will inquire its 2-hop neighbors for lending a subtree of free address space. We also propose a light-weight routing to support one-to-one routing in this environment.

Index Terms—addressing, address borrowing, routing, wireless sensor network, ZigBee

I. INTRODUCTION

Wireless sensor networks (WSNs) have attracted a lot of attention. Recently, research efforts have been dedicated to power management [9], routing [6], deployment and coverage [2], and localization [1]. Nowadays, many WSN systems have adopted ZigBee [10] as their communication protocol. ZigBee adopts the physical (PHY) and the medium access control (MAC) layers defined by IEEE 802.15.4 [5] and extends to network, application, and security services. ZigBee supports three network topologies, star, tree, and mesh. Regardless of network topology, there is a *coordinator* responsible for initializing, maintaining, and controlling the network. Star networks can only cover small areas, but tree and mesh networks can cover larger fields by allowing multi-hop communications. The backbone of a tree/mesh network is formed by one coordinator and multiple *routers*. An *end device* must associate with the coordinator or a router. In a tree network, routing can be done in a stateless manner based on nodes' 16-bit short addresses.

To form a ZigBee network, addressing is the first work to be done. ZigBee suggests a *distributed address assignment mechanism (DAAM)*, which enforces some addressing rules. By this mechanism, the coordinator needs to decide three parameters: the maximum number of children of a router (C_{max}), the maximum number of child routers of a router (R_{max}), and the maximum network depth (L_{max}). While simple, the scheme may prohibit a node from accepting isolated child routers/devices. A node is an *orphan node* when it cannot associate with any parent router but there is still unused address space in the network. Some heuristics algorithms are

proposed to reduce orphans [7].

Reference [3] proposes an address borrowing scheme. When a new node sends an association request to a router of a ZigBee network and this router does not have any free address, it will ask other neighboring routers to lend an unassigned address to serve the new node. Park et al. [8] propose a distributed borrowing addressing scheme (*DBAS*) by allowing a parent node to borrow a maximum unused address space to alleviate the orphan problem.

The main goal of our work is to alleviate the orphan problem by a distributed address assignment scheme with address borrowing. We improve the borrowing scheme of [8] by allowing a parent router to borrow a flexible subtree of address space from a neighbor. We also define the detailed procedure for our address-borrowing scheme, which is compatible with the ZigBee standard. Our solution solves addressing and routing issues altogether. When a new node tries to associate with a parent router with no unassigned address, the new node will estimate the number of orphan nodes in its neighborhood and this parent router will ask its 2-hop neighbors to lend a suitable address space to serve the new node. Then this new node can use the ZigBee DAAM to serve its children. We also show that routing and maintaining the borrow and lend lists can be easily done.

II. OVERVIEW OF IEEE 802.15.4 AND ZIGBEE STANDARDS

IEEE 802.15.4 [4] specifies the physical and data link protocols for *low-rate wireless personal area networks (LR-WPAN)*. IEEE 802.15.4 devices are classified as *full function devices (FFDs)* and *reduced function devices (RFDs)*. IEEE 802.15.4 supports star and peer-to-peer topologies. In each *personal area network (PAN)*, one device is designated as the *coordinator*, which is responsible for maintaining the network. A FFD has the capability of serving as a coordinator or associating with an existing coordinator/router and becoming a router. A RFD can only associate with a coordinator/router and cannot have children.

In ZigBee, address assignment is done in a distributed manner. To form a network, the coordinator determines C_{max} , R_{max} , and L_{max} first. Note that the children of a router include both routers and end devices. So $C_{max} \geq R_{max}$ and up to $C_{max} - R_{max}$ children must be end devices. Addresses are assigned in a top-down manner. The coordinator takes 0

“borrowed”. For example, in Fig. 2, $s_z = \text{“borrowed”}$ since $A_z = 107$ is borrowed from the coordinator. Since A_y is a child of A_z , $s_y = \text{“borrowed”}$, too. On the other hand, A_w is not a borrowed address, so $s_w = \text{“original”}$.

Fig. 2. An example of depth in the ZigBee tree Z formed by ABS with $C_{max} = 4$, $R_{max} = 3$, $L_{max} = 4$, and $B_{max} = 2$.

2) *Associating Scheme*: To start a new network, a coordinator t first sets the following parameters: C_{max} , R_{max} , L_{max} , and B_{max} . Then t assigns $A_t = 0$, $d_t = 0$, and $s_t = \text{“original”}$, and sets $R(t)$, $E(t)$, $B_r(t)$, $B_e(t)$, $L_r(t)$, and $L_e(t)$ as empty sets. The detailed associating scheme is presented below.

(a) **Router v receiving a *MLME-ASSOCIATION-REQ* request from a node u :**

- (i) If u is a router and $|R(v)| < R_{max} - |L_r(v)|$, then v finds an index l , $0 \leq l < R_{max}$, such that the address $A_u = A_v + C_{skip}(d_v) \cdot l + 1$ is free, and assigns the address A_u to u by replying a *MLME-ASSOCIATION response* with A_v , d_v and s_v to u . Then v updates $R(v)$ as $R(v) \cup \{A_u\}$.
- (ii) If u is an end device and $|E(v)| < C_{max} - R_{max} - |L_e(v)|$, then v finds an index l , $0 \leq l < C_{max} - R_{max}$, such that the address $A_u = A_v + R_{max} \cdot C_{skip}(d_v) + l + 1$ is free, and assigns A_u to u by replying a *MLME-ASSOCIATION response* with A_v , d_v and s_v to u . Then v updates $E(v)$ as $E(v) \cup \{A_u\}$.
- (iii) Otherwise, if $|B_r(v)| + |B_e(v)| \leq B_{max}$ and $s_v = \text{“original”}$, v notifies u its d_v and asks u to issue a request *Borrowing-REQ* if u desires to connect to the network.
- (iv) If steps (i), (ii) and (iii) all fail, v ignores the

request.

- (b) **Node u receiving a *MLME-ASSOCIATION response* containing d_v and s_v from node v :** Node u updates its network address A_u , sets $p(u)$ as A_v , d_u as $d_v + 1$ and s_u as s_v , and joins as v 's child.
- (c) **Node u receiving a response from v containing d_v referring u to issue a request *Borrowing-REQ*:**
 - (i) If u is a FFD, then it sends an *Orphan-Count-REQ* with value $d = \min\{L_{max} - (d_v - 2), L_{max} - 1\}$ to its d -hop neighbors to compute $o(u)$ by accumulating *Orphan-REPs*. Then it sets $o(u)$ as $o(u) + 1$ and sends a *Borrowing-REQ* with the desired address space of $o(u)$ to v .
 - (ii) If u is a RFD, it sends a *Borrowing-REQ* with the desired address space of $o(u) = 0$ to v .
- (d) **Node x receiving an *Orphan-Count-REQ* with a value d :** If x is an orphan node and it is the first time that x receives this packet, then x sends a *Orphan-REP* to the source node first and x rebroadcasts an *Orphan-Count-REQ* to its neighbors with the value $d + 1$ if x is a FFD and $d + 1 < L_{max}$. Otherwise, x ignores the request.
- (e) **Router v receiving a *Borrowing-REQ* with the desired address space of $o(u)$ from a node u :**
 - (i) Router v sends an *ASK-ADD-REQ* with the value $h = 0$ and the value $o(u)$ to its ancestors and descendants which are in v 's 2-hop neighbors.
 - (ii) When router v receiving *ASK-ADD-REPs* with free address spaces, v selects one whose free address space f is the closest to $o(u)$ and then updates $B_r(v)$ if u is a FFD ($o(u) > 1$). If u is a RFD ($o(u) = 0$), it selects the address whose depth is the smallest and updates $B_e(v)$.
 - (iii) Then v sends this address or address space with its depth by replying a *MLME-ASSOCIATION response* with A_v , d_v and the value $s_v = \text{“borrowed”}$ to u and sends an *ASK-ADD-Confirm* with the borrowing address A_y to the lender.
- (f) **Router x receiving an *ASK-ADDR-REQ* with the value h and the value $o(u)$:**
 - (i) If it is the first time that x receives this packet and $s_x = \text{“original”}$, then x checks its address space and rebroadcasts an *ASK-ADDR-REQ* to its neighbors with the value $h + 1$ if $h + 1 < 2$.
 - (1) If $o(u) > 1$ and $|R(v)| < R_{max} - |L_r(v)|$, then x finds an index l , $0 \leq l < R_{max}$, such that the address $A_y = A_x + C_{skip}(d_x) \cdot l + 1$ is free, and replies an *ASK-ADD-REP* with d_x , A_y , and the value $f = C_{skip}(d_x)$ to the source node.
 - (2) If $o(u) = 0$ and $|E(x)| < C_{max} - R_{max} - |L_e(x)|$, then x finds an index l , $0 \leq l < C_{max} - R_{max}$, such that the address $A_y = A_x + R_{max} \cdot C_{skip}(d_x) + l + 1$ is free, and replies an *ASK-ADD-REP* with d_x , A_y , and the value $f = 0$ to the source node.

(ii) Otherwise, x ignores the request.

- (g) **Router x receiving an ASK-ADD-Confirm with the lending address A_y from router v :** Router x updates $L_r(x)$ if this address would be assigned to a child router; otherwise, it updates $L_e(x)$.

In the example of Fig. 1(b), z lends address 36 to y , so its lend list $L_r(z) = \{(36, y = 54)\}$. On the other hand, y should update its borrow list $B_r(y) = \{(36, z = 1, 1)\}$. Fig. 3 shows the flow chart for an orphan node x to request a router node v to lend an address block to serve it.

Fig. 3. The flow chart of borrowing address.

Next, we analyze the depth of the ZigBee tree after borrowing. Since we do not allow recursive borrowing and a node can only inquire its 2-hop neighbors for borrowing, the maximum depth of the ZigBee tree formed by ABS is $L_{max} + 2$.

3) **Disassociation Scheme:** When a node wants to disassociate with its parent router, it should broadcast a *MLME-DISASSOCIATION request* to its parent and descendants to ensure that its address block can be re-used and its descendants can try to reassociate with other parents. The detailed disassociating scheme is presented below.

- **Node v receiving a MLME-DISASSOCIATION request from node u :**

- If u is v 's child, then v removes u from $R(v)$, $E(v)$, $B_r(v)$, and $B_e(v)$. If this address is a borrowed one, then v sends a *Return-ADD* with the address A_u to its original lender. This address A_u then can be re-used by other nodes.
- If u is v 's parent, then v sends a *MLME-DISASSOCIATION request* to its children. Since v

is not an orphan, it should try to reassociate with the ZigBee network.

- Otherwise, v ignores the request.

- **Router x receiving a Return-ADD with A_u from node v :** Then x removes A_u from $L_r(x)$ and $L_e(x)$.

Fig. 4 shows the flow chart of the above procedure.

Fig. 4. The flow chart of disassociation and address returning.

C. Routing Scheme with Address Borrowing

With the above address borrowing scheme, ZigBee can still support very simple address-based routing as follows. When router v receives a packet with a destination address A_{dest} , it accepts the packet if $A_v = A_{dest}$. Otherwise, v forwards this packet as follows.

- If $dest$ is a child router or grandchild of v , then v forwards this packet to a router as follows.
 - If $A_v < A_{dest} \leq A_v + R_{max} \cdot C_{skip}(d_v)$, v calculates A_r as $A_v + 1 + \left\lfloor \frac{A_{dest} - (A_v + 1)}{C_{skip}(d_v)} \right\rfloor \cdot C_{skip}(d_v)$. Then v forwards this packet to its child router A_r if $A_r \notin L_r(v)$; otherwise, v forwards this packet to the borrower who borrows A_r from v .
 - If $A_x \leq A_{dest} \leq A_x + R_{max} \cdot C_{skip}(d_x)$ for some node x in $B_r(v)$, v forwards this packet to its child router x .
- If $dest$ is a child end device, then v forwards this packet to one of its child end device as follows.
 - If $A_v + R_{max} \cdot C_{skip}(d_v) < A_{dest} < A_v + C_{skip}(d_v - 1)$, v forwards this packet to its child end device A_{dest} if $A_{dest} \notin L_e(v)$; otherwise, v forwards this packet to the borrower who borrows A_r from v .
 - If $A_{dest} \in B_e(v)$, v forwards the packet to this child end device.
- Otherwise, v forwards the packet to its parent $p(v)$ if v is not the coordinator, and v ignores this packet if v is the coordinator.

Fig. 5 is an example that a packet is transmitted from node 108 to node 45. This packet is transmitted to node 0 in accordance with the step 3) of the routing scheme first. Then node 0 forwards it to node 1 according to the step 1.a) of the routing scheme. Node 1 finds that address 45 should be one of its grandchildren, and this address is lent to node 54. According to the step 1.a), node 1 then forwards this packet to node 54 by looking address 45 up in the lend list of node

Fig. 5. An example of the routing transmitted from node 108 to node 45 on the ZigBee tree formed by ABS.

1. When node 54 receives the packet, it looks this address up in the borrow list and then forwards it to the child router 36 according to the step 1.b). Finally node 36 forwards this packet to node 45 in accordance with the step 1.a).

IV. SIMULATION RESULTS

To verify the benefit gained from our ABS, we evaluate the average number of orphans of our scheme as compared to other approaches. We assume the following simulation environment. The monitoring region is $500 \times 500m^2$ where 2000 routers are randomly deployed and the coordinator is set in the center. The communication range of each router is set to $50m$.

For comparison, we design three modifications of our ABS by relaxing the borrowing strategy in the step (e) of associating scheme. A parent router can ask for borrowing from its 1-hop neighbors (ABS-1), 2-hop neighbors (ABS-2), and 3-hop neighbors (ABS-3). We also set DBAS-1 and DBAS-2 as the strategies of asking its 1-hop, and 2-hop neighbors, respectively.

We vary the maximum network depth (L_{max}) to see how this influences the average number of orphans. We set $B_{max} = 2$. Fig. 6(a) shows the results. The average number of orphans is inversely proportional to the tree depth limit L_{max} . Regardless of L_{max} , our schemes always outperform other approaches. The average number of orphans by ABS-2 is fewer than that by ABS-1, since ABS-2 can serve further nodes.

Fig. 6(b) shows the average number of orphans with different R_{max} . Regardless of borrowing strategy, the higher $R_{max} = C_{max}$ makes nodes join the network more easily, and thus fewer orphans.

ABS always outperform DBAS, because it allows a parent router to borrow a flexible address space through counting orphans. On the contrary, DBAS always lets a parent router borrow a maximum address space, exhausting address quickly.

Finally, we measure the impact of B_{max} on the average number of orphans. B_{max} affects the number of children that

Fig. 6. The average number of orphans with different R_{max} .

a router can serve in the ZigBee tree. In Fig. 7, we observe that larger B_{max} cause fewer orphans.

Fig. 7. The average number of orphans with different B_{max} .

V. CONCLUSIONS

To relieve the orphan problem in a ZigBee network, we have proposed the address-borrowing scheme (ABS) by allowing a node to borrow unused address spaces from neighbor nodes. We have shown that it effectively decreases the number of orphans in a ZigBee network when the network cannot expand due to the constraints of C_{max} , R_{max} , and/or L_{max} . The unit of lending/borrowing is a subtree of address space under the original definition in ZigBee, thus reducing the cost of routing tables and the requirement of storage spaces in router nodes. We have also suggested a light-weight routing algorithm for ABS which follows the original ZigBee address-based routing strategy with a slight modification. In addition, the maximum depth of the ZigBee network is predictable. Simulation results also show that ABS can benefit original ZigBee address assignment mechanism and thus effectively reduces orphans.

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